GUIDELINES FOR THE COMPARISON OF HUMAN AND HUMAN ANALOGUE BIOMECHANICAL DATA

Report of Guidelines Subcommittee

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INTRODUCTION

The discipline of biomechanics is a diverse activity encompassing study of a wide variety of species and applied problems. Biomechanical studies are conducted in many organizations by investigators with various backgrounds. Impact biomechanics has received attention primarily because of high mortality rates associated with impacts sustained in automobile accidents. A major goal is to delineate the mechanisms of impact-caused injuries. An essential activity is measurement of mechanical data from impact experiments and observations of accidental impacts on human and human analogue subjects. The central purpose of this report is to develop guidelines to ensure precise comparison of the mechanical data from diverse studies of impact events on human subjects and human analogues.

BACKGROUND

This report presents and discusses guidelines for comparison of biomechanical data dealing with the mechanics of injury responses and undesirable physiological responses in man. Although this approach is not strictly intended for other important and expanding areas of biomechanics dealing with ambulation, prosthetics, and specialized environments of altered gravitational forces, it is applicable to those other areas.

Many aspects of injury phenomena have been described or predicted from accident investigations, medical records, experimental simulations, and theoretical analyses. In all cases the subject of observation is a human or a human analogue. The agent of the injury is the mechanical event operating on the subject. As with all agents causing deleterious effects on human subjects, experiments designed to reproduce the injuries cannot use human subjects. Therefore, particular types of injury have been studied by a variety of indirect means, using various animal species or other human analogues. Another indirect approach has been to use volunteer human subjects in experiments designed to measure certain human tolerances. Further understanding has been derived from the epidemiology of accidents involving impact forces. Discerning limits from these efforts has been a continuing effort of expert judgment. The validity of these judgments is subject to continual review as more data are compiled. All of these efforts involve continued comparison and reexamination of data. The basic purpose of this committee report is to improve the precision of this comparative effort. This is considered to be an elementary step in forming a mutually consistent and common data base of information pertaining to the mechanisms of injury in man.

Attempts to construct a single inclusive data base concerning the effects of mechanical forces on man from a wide diversity of experiments and subject species present a major dilemma. There are several types of data to be considered:

1. Description of the experimental subject.

2. The mechanical variables in the environment to which the subject is exposed.

3. The mechanical, physiological, and injury responses of the subject.

Careful definition and description of the coordinate systems used to measure and communicate the mechanical data is a necessary first step to be undertaken if effective comparisons of numeric data are to be undertaken. The mechanical forces applied to the man and the resulting forces existing at various points in the anatomy constitute the input variables that cause the physiological and injury response. Ambiguities or inconsistencies in measuring or reporting the mechanical data will result in ambiguities in describing the etiology of the resulting injuries. Furthermore, methods of describing and comparing mechanical data are well developed in the physical sciences and need only to be systematically applied to biomechanics. For this application, these guidelines are proposed in an attempt to assure adequate description of the geometry of the experimental subject and the attached instruments, with an appropriate reference geometry based in the laboratory.

Descriptions of the essential geometry use three-dimensional coordinate systems. The geometrical description serves as the basis for comparing mechanical data. The approach must be sufficiently general to encompass the wealth of details concerning each experimental setup, experimental subject, mechanical variable measured, instrumentation type and placement, and force applicator. In large numbers of experiments, the geometry of major components of the experiment is invariant. In others, the geometry may not be invariant. But even with marked distortion of the geometry, the initial conditions of the geometry of the experiment must be available. The proposed guidelines attempt to assure complete and unambiguous description of the geometry. The stepwise approach proposed here consists of the following five guidelines.

THE GUIDELINES

The five guidelines to be followed for comparison of biomechanical data are:

1. All coordinate systems should be orthogonal and should be constructed by specifying an origin, a first and a second axis taken in order, and a third axis constructed by the right-hand rule. Variables, operations, and parameters expressed in any coordinate system should be defined by use of a right-hand rule.

2. A laboratory coordinate system, fixed to the surface of the earth (laboratory fixed), with the third coordinate axis parallel to the direction of gravity and preferably positive away from the center of the earth, should be established. In any experiment or observation, it should be possible to describe all the coordinate systems relative to the laboratory fixed system.

3. The anatomy of interest of the experimental human subject or human analogue must have an anatomically based three-dimensional coordinate system.

4. The instrumentation for mechanical measurements must have an instrumentation-based three-dimensional coordinate system described in terms of the object to which the instrumentation is attached.

5. The initial values of the experiment must be described so that all the defined coordinate systems can be expressed relative to each other.

DISCUSSION

Guideline 1.

Application of the first guideline is illustrated in Figures 1, 2, and 3. The subscripts i, j, k are used to identify the first, second, and third axes in order. The unit vector $\vec{\mu}$ is introduced simply to form the cross product as a satisfactory method of defining a right-hand rule.

Figure 3 shows an example of how the guideline is applied for purposes of defining mechanical variables, operations, and parameters. Using the stated guideline, Euler angles are defined in order about the first, second, and third axis (i, j, k) in accordance with the right-hand rule. The successive rotations are labeled E_i, E_j, E_k, and shown in Figure 3. It should be noted that there are twelve possible definitions of Euler angles. They are divided into two types. The first type is defined sequentially around each of three successive axes; there are six possibilities, depending on the order of the axis. The second type is defined as a rotation around an original axis, then around a derived axis, and finally around the original which has been rotated; again there are six possibilities. The selected definition is of the first type, using the i, j, k order. Further elucidation of this approach has been described (1). If direction cosines are used, the relationship between subscripts and coordinate systems should be defined.

Guideline 2.

Guideline 2 establishes the requirement for a single three-dimensional coordinate system to which all other coordinate systems required for impact biomechanics can be related. The coordinate system recommended by the committee for this purpose is one fixed to the surface of the earth in the laboratory, with the third axis parallel to the direction of gravity and positive away from the center of the earth. This system can be considered space fixed under the presumption that the earth motion is negligible for impact biomechanics measurements. The selection of the third axis parallel to gravity gives recognition to the fact that gravity is present in all practical experiments and observations in the area of impact biomechanics. Further, measurements by accelerometers do not differentiate the acceleration due to gravity from the acceleration due to motion relative to the laboratory-fixed coordinate system. In reporting individual experimental results, it may be convenient for the investigator or observer to use reference coordinate systems moving relative to the lab or to report the kinematics of one part of the experimental subject's anatomy relative to another. The intent of the guideline is that measurements be taken so that any of the coordinate systems defined or used in a set of observations can ultimately be expressed in the laboratory-fixed coordinate system. Figure 4 illustrates a laboratory-fixed coordinate system with two types of coordinate systems commonly used in biomechanical research. A coordinate system used to describe the experimental fixture may have linear and angular acceleration relative to the laboratory-fixed system as part of the experimental design. Furthermore, an anatomically based coordinate system of a subject attached to or interacting with the experimental fixture may have a different linear and angular acceleration relative to the laboratory-fixed system. All of these interrelationships can be derived if enough measurements are taken to express the data in a laboratory-fixed system.

Guideline 3.

This guideline describes exemplary procedures for developing anatomically-based coordinate systems located on or within the human body. These systems are necessary to define human motions on the basis of experimental data, such as that obtained from accelerometers attached to the body. It is anticipated that various parts of the anatomy will be defined and described in three-dimensional coordinate systems as new applications arise and new experiments are devised. Three parts of the body serve as examples to demonstrate the techniques and difficulties that may be encountered in developing coordinate systems--head, thorax, pelvis.

Candidate coordinate systems have been proposed for the head by Ewing and Thomas (2), Thomas (3), and Hubbard and McLeod (4). The directions of the coordinate axes are approximately the same in the two cases and are based on the Frankfort plane and a vertical perpendicular. The origins are different, with Hubbard's located at the nasion of the skull and Ewing and Thomas's located at the midpoint of a line connecting the superior edges of the left and right auditory meatus. Neither of the origins is located at the center of gravity of the head. Either coordinate system offers a sufficient framework for studying kinematics and dynamics of the skull when it is viewed as a rigid body. Figure 5 shows the anatomical points defining the system as well as head-mounted instrumentation in an x-ray view. Given sufficient kinematic data (a minimum of six independent quantities), the motion of any point on the skull can be determined.

The thorax presents a different class of problems because of its flexibility, the lack of classical landmarks relatable to the thoracic skeleton, and the difficulty of using x-ray procedures to quantify the position of the thoracic skeleton at any point in time. The only known coordinate system associated with the thoracic skeleton, other than those used for mathematical procedures (See Roberts (5)) where each bone of the thorax is defined in terms of one or more coordinate systems, has been developed by Ewing and Thomas. This coordinate system was developed to measure input kinematics to the head and neck system by following the motions of the first thoracic vertebra as a rigid body. (See Figure 6). Its origin is at the anterior-superior corner of the vertebral body. The +x axis is defined by connecting the midpoint of a line between the superior and inferior corners of a posterior spinous process to the anterior-superior corner. The +z axis is set perpendicular in a superior direction.

To account for flexibility, it may be necessary to develop similar coordinate systems for additional thoracic vertebrae. In addition, to be able to monitor motions at the front of the chest and to relate motions in one part of the chest to any other point on the chest, additional coordinate systems would be needed for the sternum, possibly based on the suprasternale and the substernale. If it is thought necessary to approximate the thorax as a rigid body or as a flexible body described approximately by using a single coordinate system, a procedure such as that proposed by Robbins (6) could be used. The steps in this procedure are:

1. Connect the first and twelfth thoracic vertebra coordinate origins with a line.

2. Connect the substernale and the suprasternale with a line.

3. Connect the centers of the two lines with a new line directed toward the front of the chest to define the directions of a +x axis.

4. Construct a perpendicular in the superior direction to define a +z-axis and a +y-axis to tne left.

The pelvis is sufficiently rigid to warrant the use of a single coordinate system. Difficulties arise because sufficient soft tissue, often of considerable delicacy, surrounds the structure and masks most bony landmarks. Candidate landmarks (most readily accessible by x-ray) are the symphysion and the right and left anterior-superior iliac spines. One of the many possible reference frames could be constructed as follows:

1. Connect the two anterior-superior iliac spines with a line.

2. Specify as the origin the center of the line.

3. Define a +x-axis as the line from the origin to the symphysion.

4. Construct an upward normal to define the +z-axis and a leftward normal to define the +y-axis.

Guideline 4.

The guideline applies to instrumentation attached to body segments which can be assumed to be rigid (such as the calvarium) and also to deformable bodies such as the thoracic skeleton and its contents. The guideline further applies to experimental fixtures and portions of the fixture that interact with or attach to the experimental subject.

The methodology for the description of instrumentation on rigid bodies requires precise determination of the instrumentation reference frame with respect to the anatomical or experimental fixture reference frame. This may be accomplished subsequent to placement of the instrumentation. This approach has been used for kinematic experiments on human subjects and experimental fixtures (Ewing and Thomas (2)).

It is often impractical and perhaps impossible in experiments involving deformable anatomy to completely measure the mechanical response. In these cases, the comparison of kinematic data gathered on deformable bodies requires that the location and orientation of instrumentation be precisely specified before its placement. This is necessary because deformation before or during the experiment may destroy the original basis used in defining the anatomical coordinate system. The following steps constitute a procedure for applying the guideline for deformable bodies.

1. Place the subject in a standard posture.

2. Define anatomical coordinate systems.

3. Mount instrumentation in a prescribed manner relative to the anatomical and experimental fixture coordinate systems that can be reproduced in future experiments.

4. Conduct the experiment after identifying the initial conditions of the instrumentation, anatomical, and experimental fixture coordinate systems as discussed in Guideline 5.

Guideline 5.

The fifth guideline requires the initial kinematic values of all of the coordinate systems used to describe the event to be measured. The initial values can be measured relative to the laboratory-fixed coordinate system or relative to another coordinate system which in turn is measured relative to the laboratory-fixed coordinate system. With this information, it is possible to express the initial values of one coordinate system relative to any other. The minimum required initial values are angular and linear acceleration, velocity, and displacement. Conceivably other initial values may be required, depending on the details of the individual experiment.

CONCLUSIONS

The committee considers that use of these guidelines in formulating human and human analogue biomechanical data is fundamental for successful comparisons of numeric data from diverse sources. If the complete description required by these guidelines is lacking for any data base, this can produce ambiguities when such a data base is compared with another data base. The committee further concludes that the use of these guidelines implies continued efforts to develop useful anatomically based coordinate systems. The effort should be the concern of a standing committee with appropriate sponsorship and having access to persons with expertise in anatomy, anthropometry, and mechanics. This approach emphasizes the importance of adequate three-dimensional descriptions of defined anatomical segments of humans and human analogues to any continuing effort to compare biomechanical data. The committee further concludes that efforts to develop standards for instrumentation placement and performance can proceed most effectively if these guidelines are followed. The ultimate goal is to formulate the exact etiology of impact-caused injuries and methods for preventing the injuries. The ability to compare the mechanical data, adequately describe and measure the anatomy, and control the instrumentation placement and performance are essential requirements for reaching this ultimate goal.

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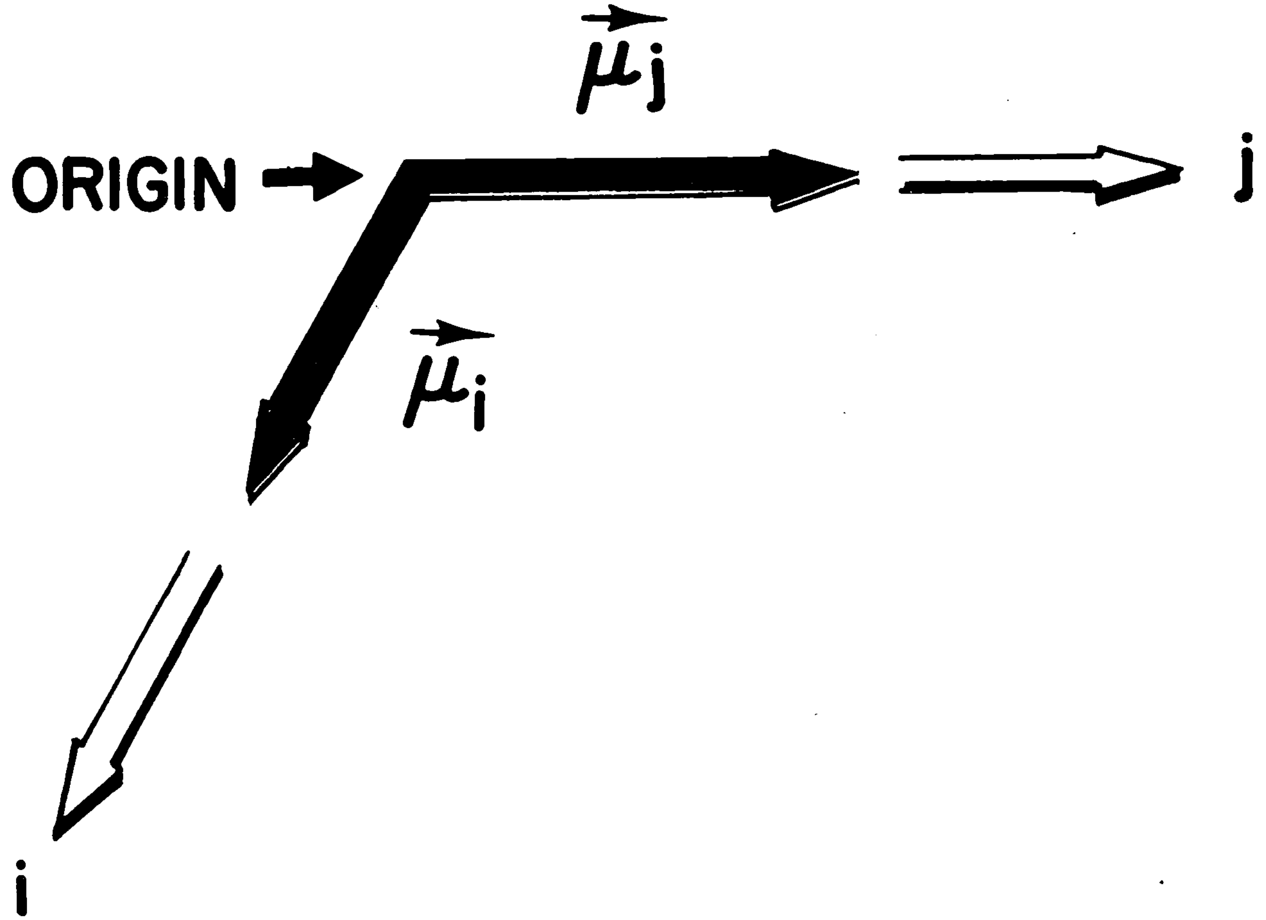


FIGURE 1. Selection of origin and first and second axes, Thomas (1).

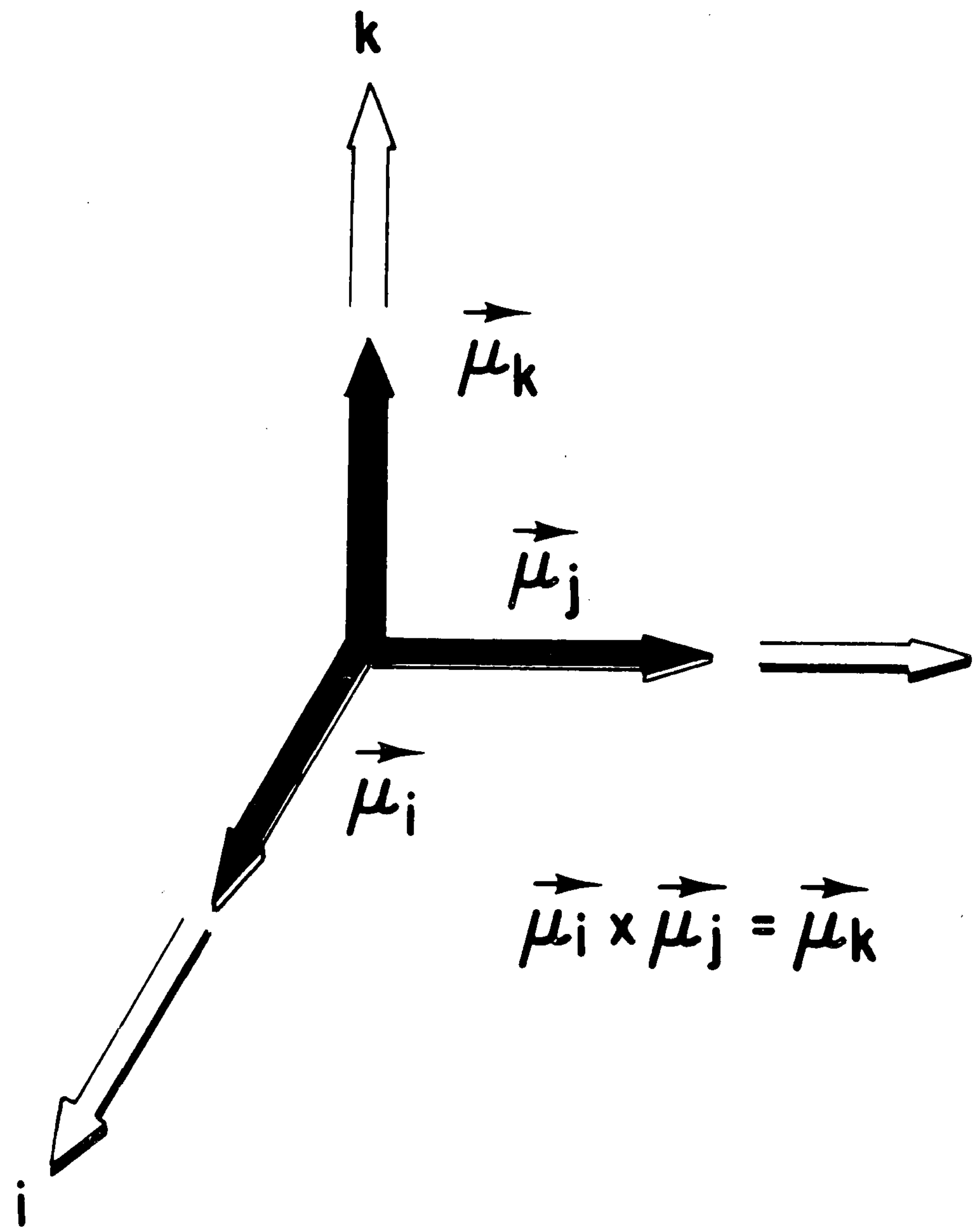


FIGURE 2. Definition of third axis (k), Thomas (1).

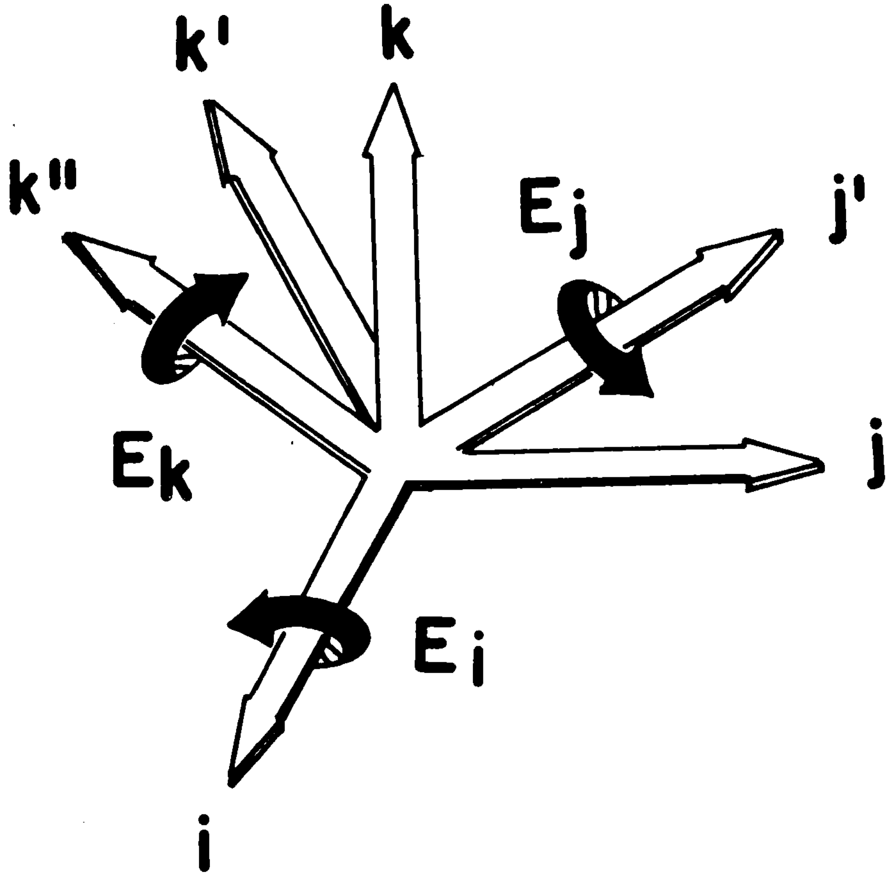


FIGURE 3. Example of the definition of Euler angles using Guideline 1, Thomas (1).

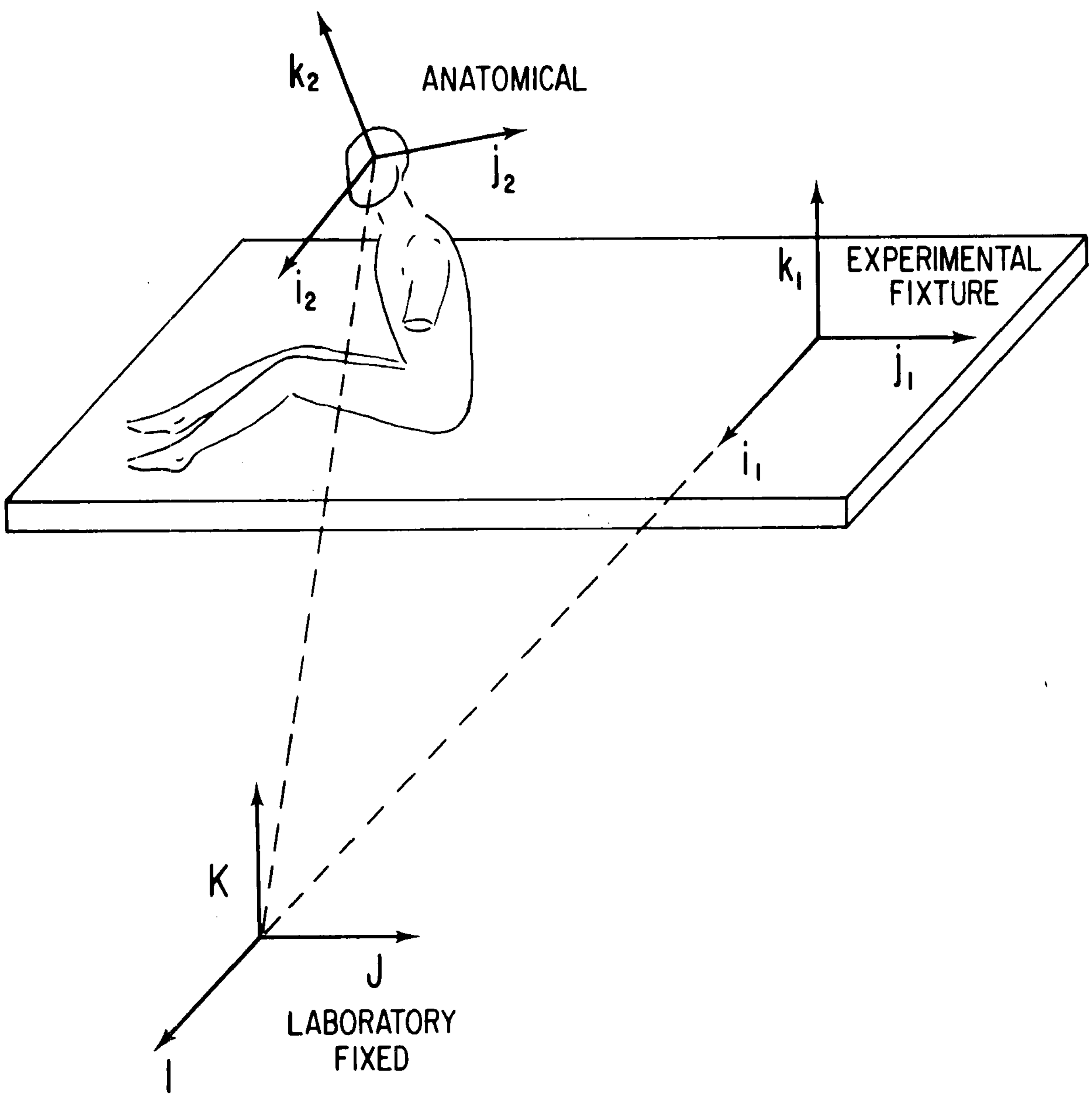


FIGURE 4. An experimental fixture, and an anatomically-based coordinate system illustrated relative to the Laboratory Fixed coordinate system.

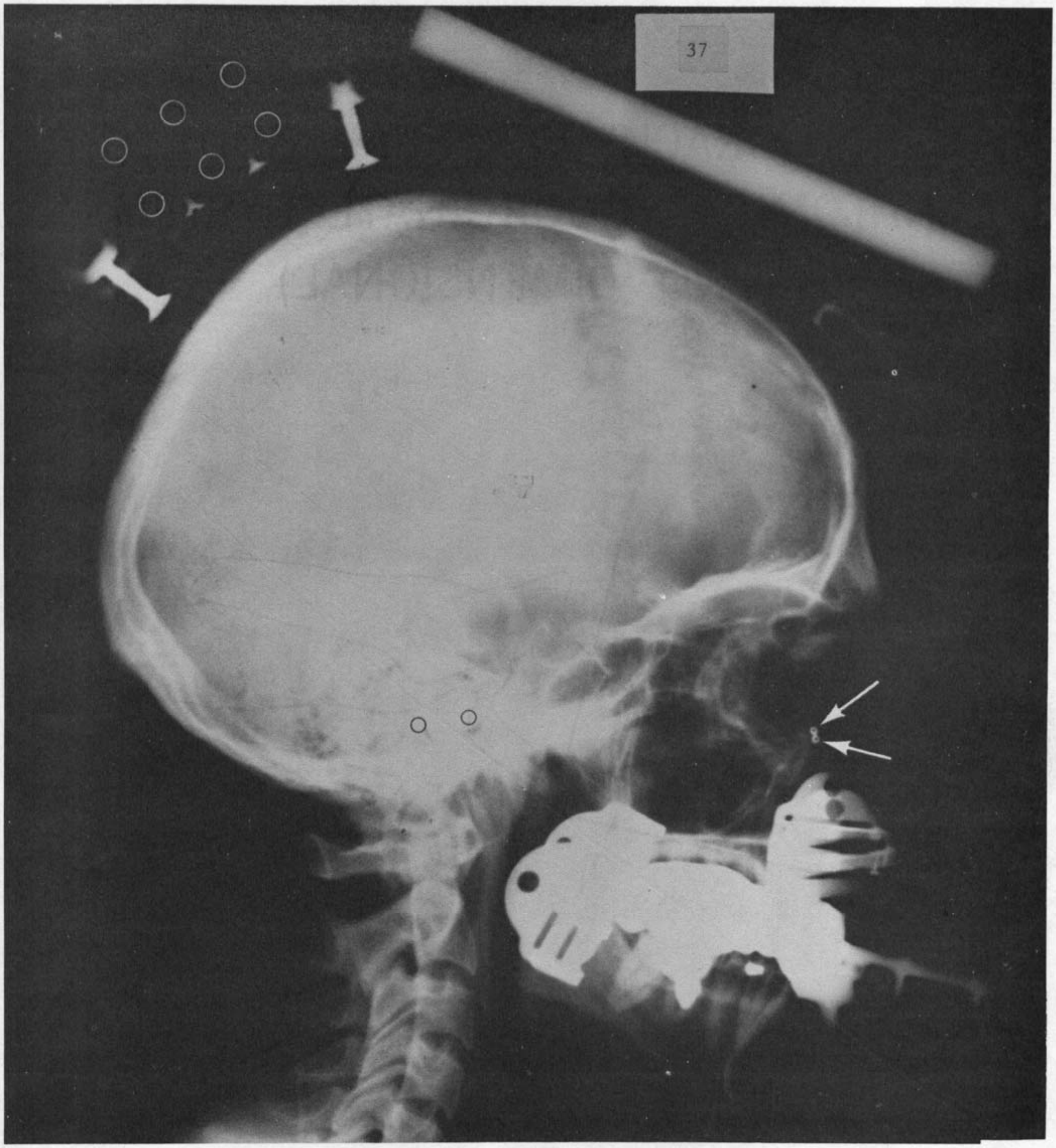
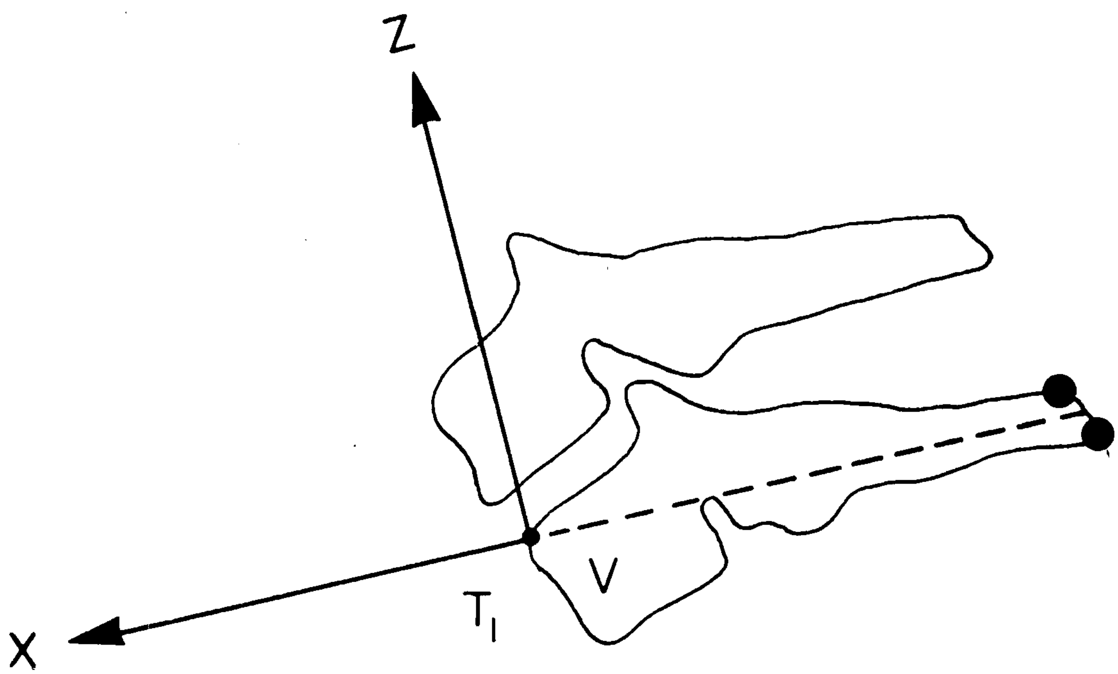


FIGURE 5. Head x-ray illustrating the basis for anatomical and instrumentation coordinate systems. Reference points are indicated by circles and arrows, Ewing & Thomas (2)

FIRST THORACIC VERTEBAL BODY (T_1) ANATOMICAL COORDINATE SYSTEM (TWO DIMENSIONAL)



T_1 = ANATOMICAL COORDINATE SYSTEMS

V = FIRST THORACIC VERTEBRA

FIGURE 6. Illustration of first thoracic vertebral body coordinate system (two-Dimensional), Thomas (3), Ewing & Thomas (2). The x axis is the first axis and the z axis is the third axis.

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